

Challenges in Determination of Brazilian Test Rock Specimens Surface Displacements by Using Digital Image Cross Correlation

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This paper was prepared for presentation at the 48th US Rock Mechanics / Geomechanics Symposium held in Minneapolis, MN, USA, 1-4 June 2014.

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ABSTRACT: The difficulties associated with applying the digital image processing techniques and in particular digital image cross correlation (DIC) to determine the surface displacements of rock specimens in Brazilian tests are discussed in this study. In recent years, advanced digital imaging tools and techniques have opened new horizons to capture and monitor surface and even internal displacement fields. DIC is a noncontact method to determine displacements between two successive digital images taken from a loaded specimen at two different strain levels. Though the fundamentals of the DIC technique seem to be simple, in practice determination of small surface displacements on rock specimens could be a challenging task due to image noise, image resolution, surface texture, etc. In this research, the effect of image resolution, camera and lens types, different surface textures, and data interpolation to reach sub-pixel accuracy were studied. The results show that results are highly sensitive to the surface texture, size of the charge-coupled device (CCD) of the camera, and employing sub pixel accuracy generates smoother displacement contours. Moreover, in case of rigid body motion of the specimen using zoom lenses does not show any significant effect on the obtained displacements.

1. INTRODUCTION

Historically, different traditional methods have been used to capture simple deformations of materials under different loading conditions. Advances in science and technology has helped industry to measure and monitor complex phenomena, which were impossible in the past. One of these new methods is non-contact measurement technique. Measurement of displacements in large or small scales and close or far ranges are possible in this method. Digital image correlation (DIC) is a common technique to compare two successive digital images taken from a loaded object to determine the displacements of many points at the same time. DIC takes advantage of comparing digital images captured by digital cameras. The main benefit of this method is its low cost, ease of use, and speed. DIC was developed in early 1980's as a method for the full-field analysis of surface strain. [1, 2]. This method is based on the calculation of surface deformation using a set of digital images of un-deformed and deformed states. The technique consists of capturing gray-scale images of a random or regular surface pattern using one or two digital cameras. The surface pattern is typically applied

in the form of randomly distributed dark speckles on top of a white/high contrast background, generating a pattern that can be easily recognized and detected. The surface pattern deforms during loading. Image facets are created within the captured images allowing for surface coordinates and deformation to be tracked from one image to the next with sub-pixel accuracy. Upon conclusion of processing, a complete strain map of the region of interest (ROI) is obtained [3, 4]. This method originally was developed as a 2D technique, which utilizes measurements from a single camera focused directly on the surface of a planar specimen undergoing planar deformations. Later the method was extended to three dimensions to capture 3D displacements [2]. Use of DIC as an analytical tool has grown rapidly in recent years as hardware and software advancements have improved its viability. However, to the best of authors' knowledge the effects of different parameters in determination of surface displacements of Brazilian rock specimens by using DIC have not been reported yet. The surface displacements of a Brazilian rock specimen are very small while the entire specimen could have a large rotation or translation during the initial stages of loading (rigid body motion). Besides, the sudden rupture

happens in relatively a very short time. These are the main challenges in applying DIC for Brazilian tests on rock specimens or similar situations. This paper presents a systematic way to study the effects of different important DIC parameters on the accuracy and quality of the obtained displacement fields.

2. MEASUREMENT OF DISPLACEMENTS BY USING DIGITAL IMAGE CORRELATION (DIC)

2.1. Methods

DIC has been used in different studies to detect displacement fields on the surface of the loaded specimens [5, 6, 7, 8]. DIC compares two successive digital images taken from a specimen under loading. The first image is known as the reference image (or template) and the second is known as the deformed (or target) image. First, a subset from the reference image is selected. Then the deformed image is searched for a subset with the same size that has the maximum similarity to the reference subset and DIC is used as a similarity criterion. The vector that connects the center of the reference subset to the deformed subset is considered as the displacement vector for the reference subset. DIC, however, may be defined or applied in different ways, including zero-normalized cross-correlation (ZNCC), normalized sum of squared difference (NSSD), and zero-mean sum of squared difference (ZSSD). Table 1 shows a summary of common correlation methods and their optimal application [2]. In this table Φ (G) is photometric transform, G is intensity distribution of the object, “b” is offset and “a” is scale.

Table 1. Summary of common DIC methods

Method	Intensity Changes	$\Phi(G)$
SSD	none	$\Phi = G$
ZSSD	offset	$\Phi = G+b$
NSSD	scale	$\Phi = aG$
ZNSSD	scale + offset	$\Phi = aG+b$
NCC	scale	$\Phi = aG$
SAD	none	$\Phi = G$

2.2. Algorithm

In this research, Matlab Computer Vision Toolbox has been used, and this toolbox comes with two different search methods, Exhaustive and Three-step. Exhaustive is a calculation-intensive method that searches the location of a reference subset in a deformed image. Then it checks the regions in the neighborhood of the deformed subset and tries to find the closest matched subset. In three-step method, step size is decreased steadily to find the best match.

Two different DIC algorithms are available in this toolbox to compare the subsets, mean square error (MSE) and mean absolute deviation (MAD):

$$MSE(d_1, d_2) = \frac{1}{N_1 \times N_2} \sum_{(n_1, n_2)} \sum_{k \in B} [s(n_1, n_2, k) - s(n_1 + d_1, n_2 + d_2, k + 1)]^2 \quad (1)$$

$$MAD(d_1, d_2) = \frac{1}{N_1 \times N_2} \sum_{(n_1, n_2)} \sum_{k \in B} |s(n_1, n_2, k) - s(n_1 + d_1, n_2 + d_2, k + 1)| \quad (2)$$

Where B is a $N_1 \times N_2$ subset of pixels, (d_1, d_2) are the coordinates of the subset center, and $S(x, y, k)$ denotes a pixel location at coordinates (x, y) in frame k . In this research, MSE method has been used to calculate the correlations in different subsets [9].

3. EXPERIMENTAL SETUP

3.1. Brazilian Test

The Brazilian test is a simple test with fast sample preparation, which was developed in Japan. It is the standard test method to measure the tensile strength of concrete [10]. Though this test is often used for brittle rocks, in this research all tests have been done on marble as its relative large ductility allows getting more displacement before the rupture. Thus, more data would be collected [11].

3.2. Equipment

To study the effect of the size of image resolution or charge-coupled devices (CCD), three different CCD sizes were used. Additionally, three prime lenses with different focal lengths were utilized in the tests to investigate the effect of the lens focal length. Axial loads were applied by a strain controlled loading frame. Three different colors including red, green, and blue (RGB) were applied to the specimens surfaces to make random textures. Fig. 1 shows the test setup. The difference between the measured displacements of the specimen using a linear variable differential transformer (LVDT) and the displacements using DIC was used to evaluate the accuracy.

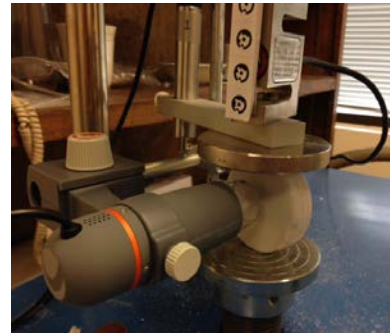


Fig.1. Brazilian test setup with a digital microscope.

4. RESULTS

4.1. Effect of the CCD Size and Focal Length of the Lens

Several tests were conducted to evaluate the effect of the image resolution that is affected by different CCD sizes and different lens focal lengths. Two digital single lens reflex (DSLR) cameras and one digital microscope were used in these tests. The CCD resolution of the digital microscope and DSLR cameras are 5 megapixels, 12 megapixels, and 21 megapixels, respectively. Fig. 2 shows the displacement contours of the 12 megapixel CCD in horizontal and vertical directions. For this case, no surface displacements were captured and the contours show a rigid body motion. Fig. 3 shows the displacement contours of the 21 megapixel CCD. The contours show a combination of rigid body motion/rotation and surface displacement.

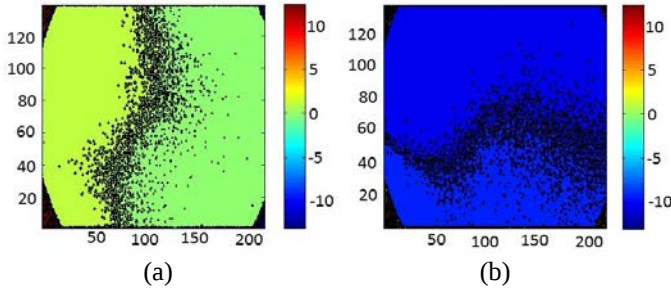


Fig. 2. (a) Displacements in horizontal direction using a 12 megapixel CCD (b) displacements in vertical direction using a 12 megapixel CCD.

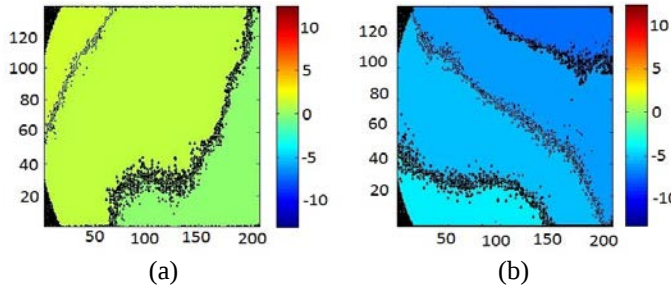


Fig. 3. (a) Displacements in horizontal direction using a 21 megapixel CCD (b) displacements in vertical direction using a 21 megapixel CCD.

The effect of the lens focal (f) length was investigated by comparing the results of three different lenses on the 21 megapixel DSLR camera, ranging from 70 mm to 2800 mm. Fig. 4 shows the results of the different focal lengths on the calculated displacements, which ranged from no detected displacement (Fig. 4) to rigid body motion (Fig. 5). The best results were achieved using the 5 megapixel digital microscope, and therefore, it was used for the rest of the tests.

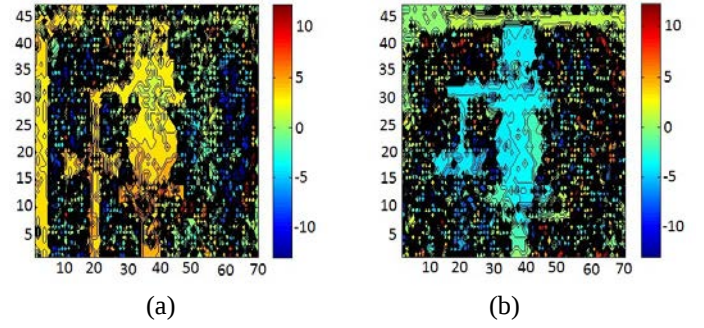


Fig. 4. (a) Displacements in vertical direction using a 12 megapixel CCD ($f = 2800$ mm) (b) displacements in horizontal direction using a 12 megapixel CCD ($f = 2800$ mm).

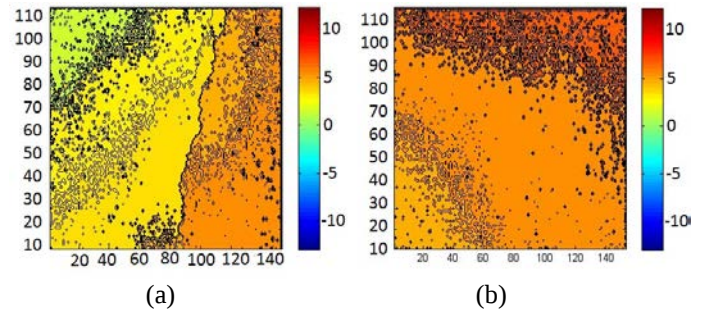


Fig. 5. (a) Displacements in horizontal direction using a 12 megapixel CCD ($f = 70$ mm) (b) displacements in vertical direction using a 12 megapixel CCD ($f = 70$ mm).

4.2. Effect of Subset Size

The sizes of the reference subsets show a significant effect on the noise associated with the results. Smaller subsets showed a better accuracy but more noise. However, accuracy of the results decreased with increasing the subset size while the noise was reduced. Figs. 6 through 10 show the effects of the reference subset size on the calculated displacements.

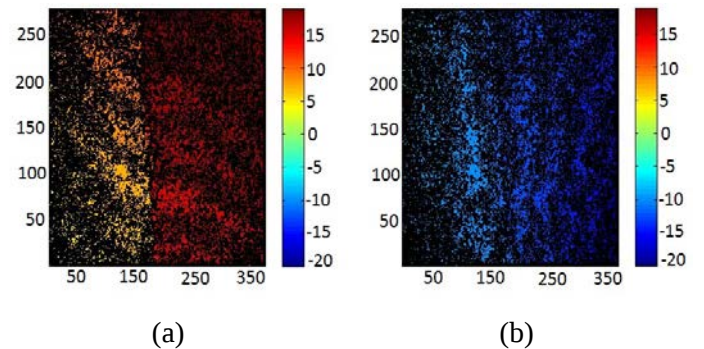


Fig. 6. (a) Vertical displacements (b) horizontal displacements using a reference subset size of 9×9 pixels.

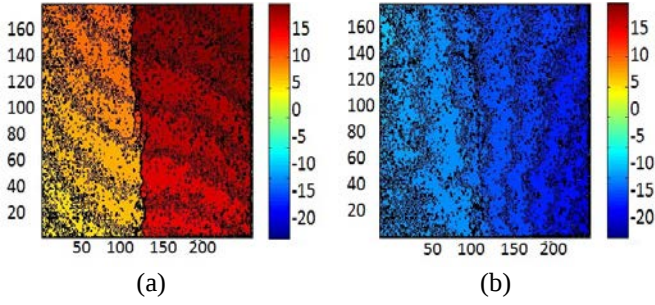


Fig. 7. (a) Vertical displacements (b) horizontal displacements using a reference subset size of 11×11 pixels.

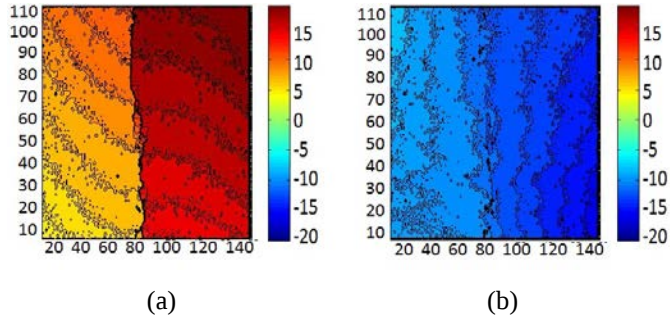


Fig. 8. (a) Vertical displacements (b) horizontal displacements using a reference subset size of 17×17 pixels.

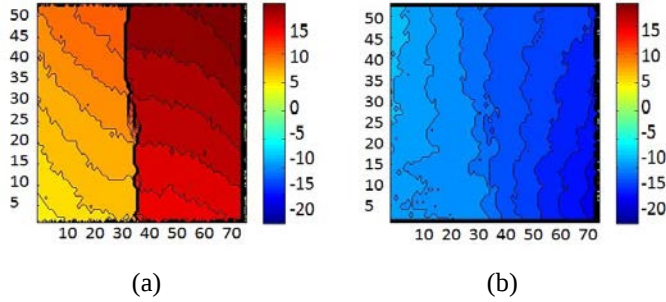


Fig. 9. (a) Vertical displacements (b) horizontal displacements using a reference subset size of 47×47 pixels.

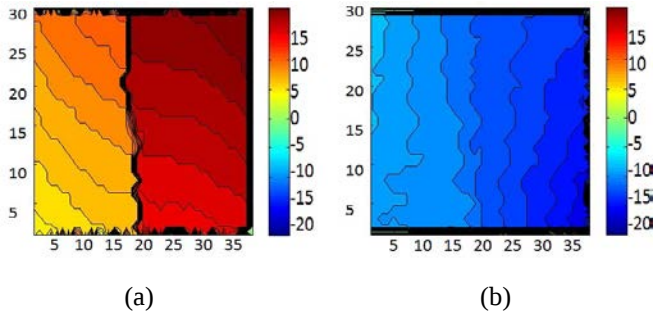


Fig. 10. (a) Vertical displacements (b) horizontal displacements using a reference subset size of 67×67 pixels.

4.3. Effect of Surface Texture

To analyze the effect of surface texture, a Matlab code was developed to process the images of different textures to find the variance of the areas of different colors. Greater variance in surface texture can reduce noise, and therefore, smaller subsets can be used to achieve a better accuracy. Fig. 11 shows the results of a surface texture analysis. Smaller average size and larger variance would help to reach smaller subset size.

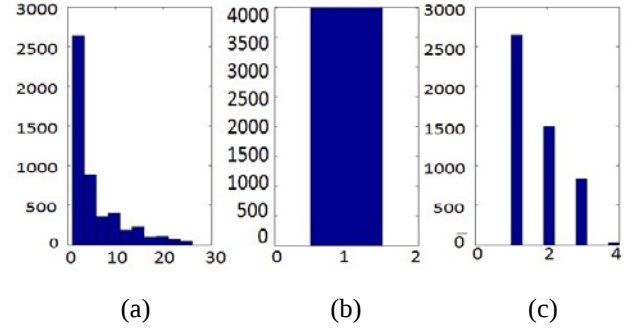


Fig. 11. (a) Histogram of the area of the paint spots (red color) (b) Histogram of the area of the paint spots (green color) (c) Histogram of the area of the paint spots (blue color). Horizontal and vertical axes represent area in pixel^2 and frequency, respectively.

4.4. Effect of data interpolation

Several tests were conducted to find the effect of the linear data interpolation. The major benefits of this method includes to get sub pixel accuracy and to have smoother contours. By running the same algorithm on interpolated data, the best accuracy of the method is still one pixel. However, each pixel represents a smaller area. If the size of subset and search region both scale up with a linear data interpolation, noise reduces while the accuracy of the results remains unchanged. Figs. 12 through 14 show the results of a linear data interpolation on one test.

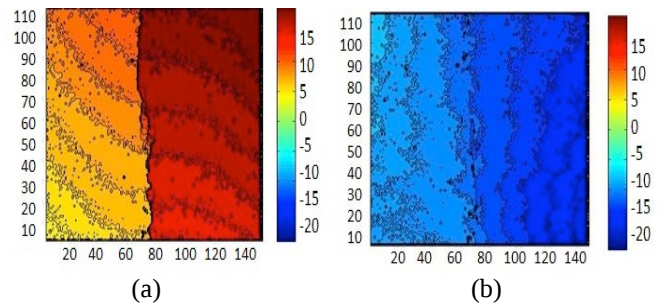


Fig. 12. (a) Vertical displacements (b) horizontal displacements without any data interpolation; subset size= 17×17 pixels, search region=20 pixels.

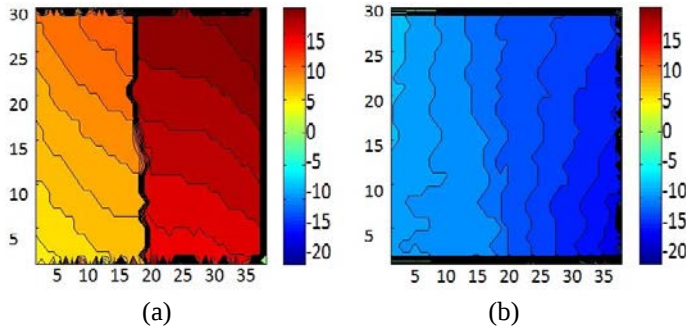


Fig. 13. (a) Vertical displacements (b) horizontal displacements without any data interpolation; subset size=67×67 pixels, search region= 20 pixels.

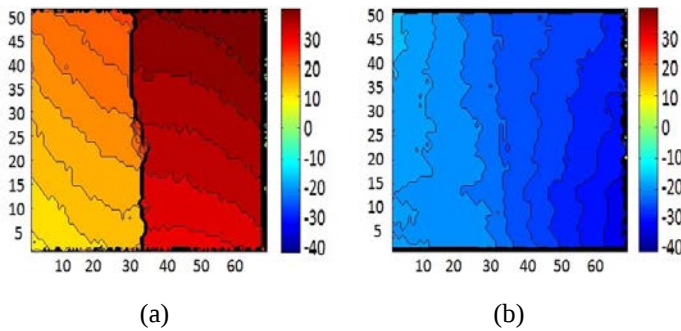


Fig. 14. (a) Vertical displacements (b) horizontal displacements using a linear data interpolation; subset size=47×47 pixels, search region= 50 pixels.

5. CONCLUSION

DIC method was used to detect surface displacements of the Brazilian rock specimens. The effects of the CCD size, lens focal length, reference subset size, texture, and linear data interpolation were studied and the results showed that the image area that is covered by each pixel (a function of lens focal length and CCD resolution) has the most significant effect on the accuracy of the final results. It means that to detect small surface displacements using DIC the microscope provides better results and an increase in microscope's CCD resolution would improve the results significantly. An increase in the reference subset size reduces the noise as well as accuracy of the results and vice versa. A linear data interpolation will provide smoother contours while it does not have any effect on the accuracy.

REFERENCES

1. Peters, W.H. and W.F. Ranson. 1982. Digital Image techniques in experimental stress analysis. *Optical Engineering*. 21(3):427-431.
2. Sutton, M.A and J. Orteu. 2009. *Image Correlation for Shape, Motion and Deformation Measurements*. 1st edition, USA.
3. Chen, J., G. Xia, K. Zhou, G. Xia and Y. Qin. 2005. Two-step digital image correlation for micro-region measurement. *Optics and Lasers in Engineering*. 43: 836–846.
4. Mathieu, F., F. Hild, and S. Roux. Identification of a crack propagation law by digital image correlation. *International Journal of Fatigue*. 36: 146–154.
5. Lin, Q. and J.F. Labuz. 2013. Fracture of sandstone characterized by digital image correlation. *International Journal of Rock Mechanics & Mining Sciences*. 60: 235–245.
6. Chen, J., X. Zhang, N. Zhan, and X. Hu. 2010. Deformation measurement across crack using two-step extended digital. *Optics and Lasers in Engineering*. 48: 1126–1131.
7. Decreuse, P.Y., S. Pommier, M. Poncelet, and B. Raka. 2012. A novel approach to model mixed mode plasticity at crack tip and crack growth. Experimental validations using velocity fields from digital image correlation. *International Journal of Fatigue*. 42: 271–283.
8. Zhang, R. and N.L. He. 2012. Measurement of mixed-mode stress intensity factors using digital image correlation method. *Optics and Lasers in Engineering* 50: 1001–1007.
9. MathWork. 2000-2012. *Computer Vision System Toolbox User's Guide*.
10. Japanese Industrial Standard A 1113. 1951. Standard Method of Test for Tensile Strength of Concrete.
11. Kourkoulis, S.K., Ch.F. Markides, and P.E Chatzistergos. 2013. The standard Brazilian disk test as a contact problem. *International Journal of Rock Mechanics & Mining Science*. 57: 132-141.